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Shielding performances of the designed hybrid laminates impacted by hypervelocity flyer ☆

Hong Wan [a,*], Shuxin Bai [a], Shun Li [a], Jianjun Mo [b], Shicao Zhao [b], Zhenfei Song [b]

[a] College of Aerospace Science and Engineering, National University of Defense Technology, Changsha 410073, PR China
[b] Institute of Fluid Physics, China Academy of Engineering Physics, Mianyang 621900, PR China

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ABSTRACT

With increasing threat of man-made debris in outer space, a shielding panel designed for spacecraft or satellite should withstand hypervelocity impact of debris, with speed up to 9.0 km/s. In this study, shielding performances of 2024 aluminum alloy panel, carbon fiber reinforced polymer composite (CFRP) panel and their hybrid laminates with different stacking configurations were investigated by ballistic tests of the materials impacted by Mylar flyer at 9.0 km/s. The results are supposed to guide the design of shielding laminate panel. It was found that the stacking combination of CFRP and aluminum alloy significantly reduced the peak shock pressure induced by hypervelocity impact, and the increase of the layer number enhanced the shielding performance of the hybrid laminate. The five-layered aluminum alloy/CFRP laminates resisted the impact of the flyer without perforation. Furthermore, the extent of the damage of an impacted laminate was related to the velocity profile on its free surface. The planar plate impact testing employing a Doppler laser velocity interferometer is a feasible approach to quantitatively evaluate the shielding performance of structural material.

1. Introduction

With increasing activities of outer space exploration, large numbers of flying debris are generated in outer space. The debris imposes realistic threat on orbital satellites and space shuttles. The most effective design for debris shielding is the Whipple structure [1], which is composed of a bumper and a rear wall with a standoff between them. But in some cases such as extravehicular activities, there is no space to place an external bumper, thus the structural panel should be able to resist the hypervelocity impact (HVI) of micro debris in space. When a thin panel is crashed by debris, shock waves are induced in the panel and the shocked zone endures an extremely high kinetic energy. Hence, how to reduce the shock intensity and to absorb the shock energy are essential concerns for the structural material which has the potential to be subjected to hyper velocity impacts during its in-service life.

Fiber reinforced polymer (FRP) composites have broad applications in many structural components for spacecrafts and military facilities due to their excellent mechanical properties and their feasibility in processing. Evaluation of FRP composite impacted by a projectile has attracted much attention in last two decades [2–7]. It is well known that the shielding capability of a composite material is determined by a combination of factors, including fabric texture, fiber/matrix interface strength and fiber performance, etc. Tennyson and Lamontagne [8] reviewed the results of hypervelocity impact tests conducted on graphite/PEEK laminates with aluminum spheres travelling at velocities between 2 and 7 km/s and reported that small changes in the stacking sequence had negligible effect on its energy absorbing ability. Fujii et al. [9] showed that the failure mode of CFRP laminates was determined by mechanical properties of the fibers and there was little difference in the absorbed energy for both cross-ply [0/90] laminates and woven laminates. Ramadhan et al. [10] suggested that adding aluminum layers into a Kevlar fiber reinforced polymer (KFRP) laminate improved its shielding performance. Hazell et al. [11–16] systemically studied the response of carbon reinforced plastic composite panel under different ballistic-loading conditions and Wang et al. [17] investigated the energy absorption efficiency of CFRP laminates with different thickness by experimental and numerical methods.

HVI of a projectile on a shielding panel brings in strong shock wave which leads to large deformation, phase transformation, fragmentation or spallation, and penetration of materials. The depiction of such complicated processes still resorts to the developing of in-site diagnostic technologies. The line-VISAR that measures velocities of the free surface of a shocked specimen instantaneously can provide the shock Hugoniot data of testing materials [18].

* Corresponding author. Tel.: +86 731 84573180; fax: +86 731 84574657.
E-mail addresses: wan66hong@yahoo.com.cn, wannhong@nudt.edu.cn (H. Wan).

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Two-stage light gas gun can launch a projectile to a speed of 7 km/s and is commonly used for ballistic tests. However, it is infeasible to study the shielding performance of a material impacted by debris with average speed of 9 km/s. Osher et al. [19] used a 100 kV electric gun to perform HVI tests and successfully accelerated a 10-cm-square Kapton flyer plate to 3.2 km/s (4.3 g in weight) and a 1.0-cm-square, 0.3-mm-thick Kapton flyer to 18 km/s. Katz et al. [20] investigated the response of composite materials to high-speed impact using laser-driven aluminum flyer at velocities from 1 to 3 km/s. In this study, the shielding performances of 2024 aluminum alloy, CFRP panel and a series of hybrid laminates consisting of aluminum alloy and CFRP (or KFRP) were examined by means of an electric gun which can launch Mylar flyer to a velocity over 9 km/s, for the purpose of guiding the design of a shielding material. The correlation between the extent of the damage and the velocity profile of the impacted target was also investigated in this paper.

2. Experimental methodology

The experimental configuration of the HVI testing is schematically shown in Fig. 1 [21]. A Mylar film (0.1 mm in thickness and 1.4 g/cm^3 in density) was bonded on the top of an aluminum bridge foil. When the bridge foil was applied a charging voltage over 20 kV, it exploded and a plasma was formed, driving the Mylar flying upward at a hypervelocity. Due to the restriction of the gun barrel mounted above the Mylar film, the flying film was cut to a bore-sized flyer and the flyer impacted a specimen above the gun barrel. In this experiment, the gun bore was 10 mm in diameter and 8 mm in depth, and the aluminum bridge foil was in dimensions of 10 mm × 10 mm × 0.1 mm. To eliminate the effect of the plasma pressure on the specimen, a 4-mm-length gap was introduced between the specimen and the upper edge of the barrel.

The flyer velocity is determined by the following equation:

$$u_f = (2kJ^n)^{1/2}(\rho_f\delta_f/\rho_F\delta_F + 1/3)^{-1/2} \quad (1)$$

Here in: u, J, ρ and δ denote velocity, the current density causing the explosion of the bridge foil, volume density and thickness, respectively. The subscript letters f and F represent the Mylar flyer and the bridge foil, respectively. k and n are Gurney constants related to the equipment. As the explosive current density J is correlated to the charging voltage of the bridge foil, the velocity of the Mylar flyer can be modulated by adjusting the charging voltage. In the experiment, the flyer was accelerated to over 9 km/s by a charging voltage of 28 kV.

A Doppler laser velocity interferometer was used to measure the free surface velocity profile of the specimen under HVI. For the CFRP panel, a piece of 10-μm-thick aluminum film was covered on the specimen's free surface as a laser reflective surface.

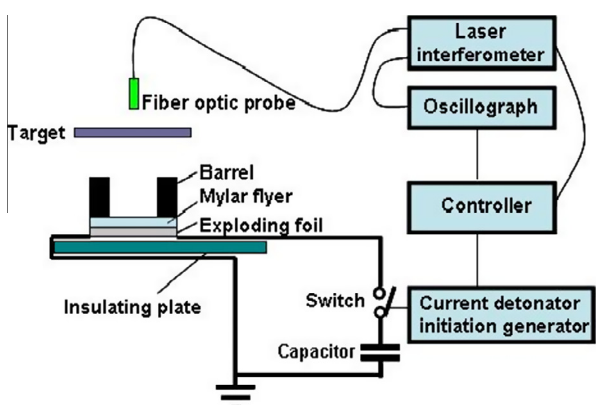


Fig. 1. Schematic configuration of the electric gun.

3. Experimental results and discussion

3.1. HIV testing on 2024 aluminum alloy and CFRP composite

To design a shielding material with an enhanced performance of resisting to HVI of micro debris, we first studied the shock responses and damage behaviors of 2024 aluminum alloy panel and CFRP panel, respectively. The CFRP panel was fabricated by a vacuum assisted resin transfer molding (VARTM) process [22] using Bisphenol A epoxy (manufactured by Balin Petrochemical Co., China) and T300 fabric cloth (manufactured by Toray Co., Japan). The volume fraction of the carbon fibers varied in the range of 45–50%. The thickness of each specimen was 5 mm.

The photographs of aluminum alloy and CFRP panels impacted by the hypervelocity Mylar flyer are shown in Figs. 2 and 3, respectively. For 2024 aluminum alloy, a holistic deformation of the panel and a newly formed fracture surface in the free surface of the impacted zone were observed (Fig. 2). It indicates that the internal

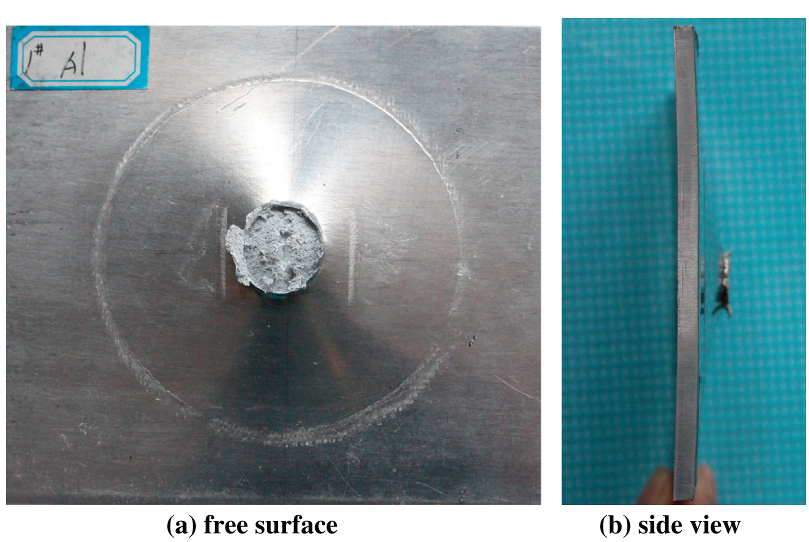
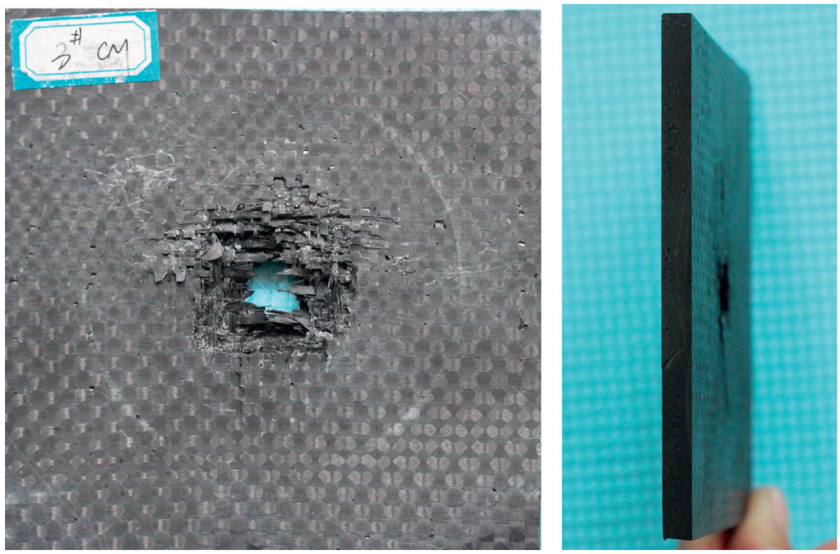
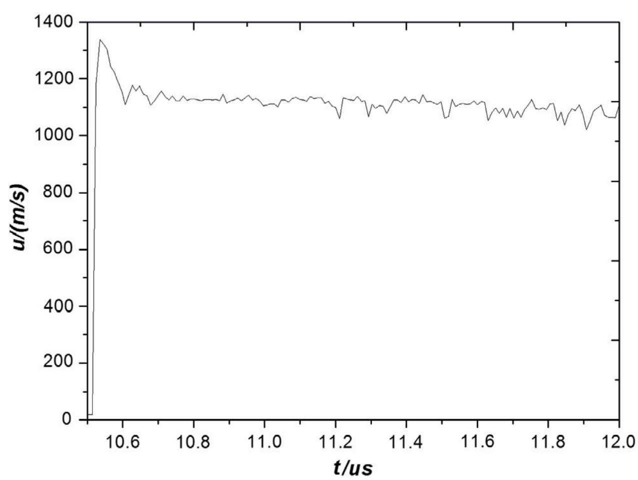


Fig. 2. Damage of the impacted 2024 alloy panel at a collision velocity of 9.2 km/s. (a) Free surface; and (b) side view.

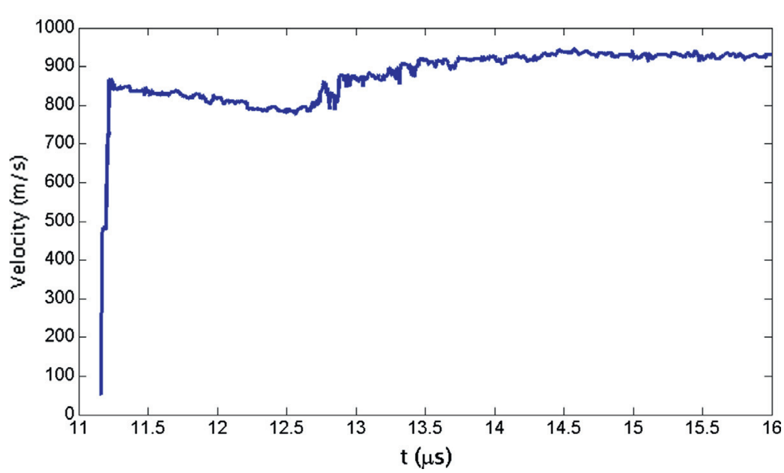


(a) free surface (b) side view

Fig. 3. Damage of the impacted CFRP panel at a collision velocity of 9.2 km/s. (a) Free surface; and (b) side view.



(a) 2024 alloy panel



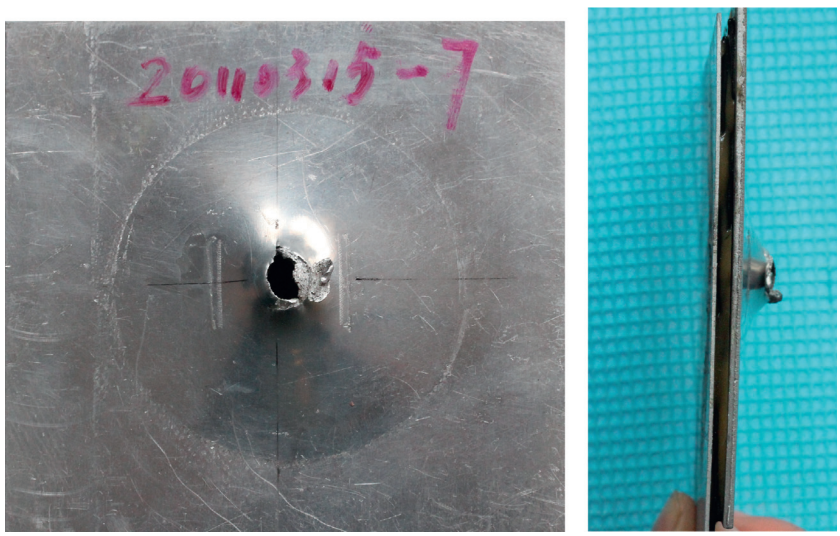
(b) CFRP Panel

Fig. 4. Measured free surface velocity profiles at the flyer speed of 9.2 km/s. (a) 2024 alloy panel; and (b) CFRP Panel.

Table 1
Configurations of HVI targets.

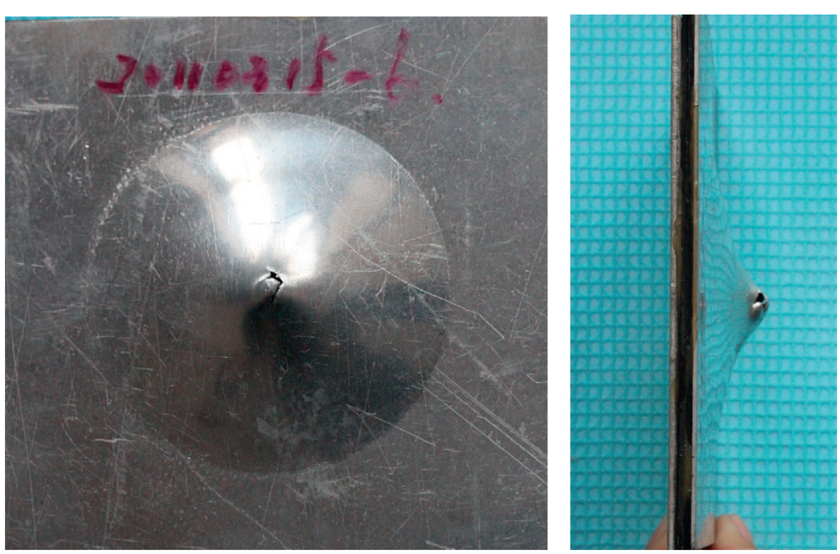
Specimen	Label	Configuration description
2024 Al alloy panel	Al	Single layer panel
Carbon fiber reinforced polymer composite	CFRP	Single layer panel
Three layered Al/CFRP hybrid laminate	1Al/2C/2Al[a] 2Al/2C/1Al	2 mm-thickness CFRP sandwiched in a 2 mm-thickness Al panel and a 1-mm thickness Al panel
Five layered Al/CFRP hybrid laminate	Al/C/Al/C/Al	1-mm-thickness Al and 1-mm-thickness CFRE stacking alternately
Five layered Al/KFRP hybrid laminate	Al/K/Al/K/Al[b]	1-mm-thickness Al and 1-mm-thickness KFRP stacking alternately

[a] The letter "C" represents carbon fiber reinforced polymer composite (CFRP) and the number before the abbreviation of a component material represents the layer thickness in millimeter. The impact faceplate (the layer experiencing the impact loading firstly) is the left layer labeled.
[b] The letter "K" represents Kevlar fiber reinforced resin composite (KFRP).



(a) free surface (b) side view

Fig. 5. Damage of the impacted 2Al/2C/Al laminate at the flyer speed of 9.2 km/s. (a) Free surface; and (b) side view.



(a) free surface (b) side view

Fig. 6. Damage of the impacted Al/2C/2Al laminate. (a) Free surface; and (b) side view.

tensile stress resulted from the impact exceeds the spall strength of the aluminum alloy and the flyer/target impacting energy is consumed mainly by the formation of the spall film and the deformation of the aluminum alloy. Fig. 3 reveals the characteristic of fragile damage with a thoroughly perforated hole and an inconspicuous deformation for the CFRP panel. In reference [8], the damage of the composite under HVI was characterized by delamination, fracture of fibers and ejecta plumes emanating from

the laminate. The impacting energy consumed by the fracture of the carbon fibers and the delamination of the laminate. Hazell et al. [14] proved that relatively thin CFRP laminate offered very little protection against high-velocity projectiles, due to the brittleness of the epoxy resin and the low strain to failure of the carbon fibers (<1%) leading to a poor trans-laminar strength.

Free surface velocity profile carries the information of the shock response of a target. Fig. 4 exhibits the measured free surface velocity profiles of the aluminum alloy panel and the CFRP composite panel impacted by the flyer. It is shown that the peak velocities of the aluminum alloy and the CFRP are 1350 m/s and 880 m/s respectively, indicating that the CFRP has the advantage of reducing the peak velocity effectively under the same flyer impact. The velocity pullback after the peak velocity in Fig. 4a is a typical indicator of the spall damage of the aluminum alloy.

The shock stress is proportional to the shock wave speed. A lower peak velocity in the CFRP panel implies a lower shock stress. Wang et al. [17] also proved that thin CFRP laminates had good energy absorption efficiency under relative higher velocity impact compared with 304 stainless steel plates.

The shock stress of a target, σ_{sp}, can be calculated by the equation as follows [23],

$$\sigma_{sp} = 1/2\rho_o D\Delta u \tag{2}$$

In which ρ_o, D, and Δu denote specimen density, shock wave speed, and velocity pullback, respectively. According to the equation, the shock stress of the aluminum alloy impacted by the flyer at 9.2 km/s is 1.75 GPa. The calculated strength is beyond the spall strength of the aluminum, which is coincident with the observation of the shocked aluminum panel in Fig. 2.

3.2. Design of hybrid laminates to improve the shield performance

In view of the spall damage of the aluminum alloy panel and the thorough perforation of the CFRP panel subjected to HVI, an improved design for a shielding panel is demanded. Based on the experimental results mentioned in former section, aluminum alloy is capable of bearing large deformation, while CFRP composite has the advantage of lowering the shock stress. Therefore, a laminate made up of aluminum alloy and CFRP composite is anticipated to improve the shielding performance on HVI.

The shielding materials were designed by stacking aluminum alloy panel and CFRP panel alternately. The merits for the hybrid stacking are as follows,

(a) Al/C/Al/C/Al (b) Al/K/Al/K/Al

Fig. 7. Damages of the impacted five layered laminates. (a) Al/C/Al/C/Al; and (b) Al/K/Al/K/Al.

(a) Al/C/Al/C/Al (b) Al/K/Al/K/Al

Fig. 8. Cross sections of the impacted five layered laminates. (a) Al/C/Al/C/Al; and (b) Al/K/Al/K/Al.

(1) To remove the peak pressure efficiently/significantly when shock wave propagated in the depth direction by proper laminate structure.
(2) To absorb the kinetic energy resulted from HVI by the deformation of aluminum panel.
(3) To withstand the tensile stress during the shock wave propagation by introducing the fiber with high strength.

To evaluate the effect of geometrical configuration on the shielding performances of hybrid laminates, two types of Al/CFRP sandwiched laminates with different layer thicknesses but the same volume fraction of the CFRP were adopted. Configurations of the designed hybrid laminates are listed in Table 1. A five layered Al/CFRP laminate consisting of three layers of aluminum alloy and two layers of CFRP was tested to examine the effect of the layer number on the shielding performance. For comparison, a five layered Al/KFRP hybrid laminate, with the same configuration as the Al/CFRP laminate, was tested. Kevlar 49 fabric cloth (manufactured by DuPont Co., USA) was used in the KFRP and the fabric volume fraction was the same as that in the CFRP. Each specimen was 5 mm thick.

3.3. Impacted damages of hybrid laminates

The kinetic energy of the flyer causes plastic deformation or perforation of the target. The competition between the plastic deformation and the perforation is dominated by the rate and the magnitude of the concentrated kinetic energy. As shown in Figs. 5 and 6, two three-layered Al/CFRP laminates has similar deformation after impact by the flyer. The specimens were perforated and no spall fractures were found on the free surfaces. It indicates that the peak pressure resulted from the impact of the flayer in the rear aluminum plate is smaller than that for a single layer aluminum panel. Since a spall film takes away a portion of kinetic energy of the flyer from the target ahead of the bulging deformation and perforation of the target, the bulge in the three layered laminates is more obvious than that in the single aluminum panel.

Fig. 7 shows that both the five-layered Al/CFRP and Al/KFRP hybrid laminates endure the impact of the flyer at 9.2 km/s successfully without perforation damage. Two lines on the free surface of the specimens were resulted from a support for Doppler laser interferometer. A relatively wider and lower bulge was formed on the rear surface of the Al/KFRP laminate, which suggested more effective mitigation of the shock energy concentration in the Al/KFRP than that in the Al/CFRP. Detailed comparison of the cross sections of the impacted specimens in Fig. 8 illustrates that the carbon fibers in the impact zone are completely fragmented while most of Kevlar fibers in the bulge area are merely bended without fracture. It can be concluded that the KFRP is superior to the CFRP in absorbing shock energy.

3.4. The free surface velocity profiles for Al/FRP hybrid laminates

Fig. 9a shows the free surface velocity profile of a three layered laminate labeled 1Al/2C/2Al impacted by the flyer. The peak velocity is 753 m/s, which is much lower than that of the aluminum alloy panel and the CFRP panel under the same impact condition. The results indicate that the shock stress induced in a three layered laminate is much lower than that in a single layer panel.

Fig. 9b and c shows the measured free surface velocity profiles of the five-layered laminates. The peak velocities of Al/C/Al/C/Al and Al/K/Al/K/Al are further reduced to 519 m/s and 327 m/s, respectively. Compared with the profile for the three-layered laminate in Fig. 9a, the five-layered laminates have the advantage of reducing the peak shock stress effectively by the introduction of two more interfaces into the targets.

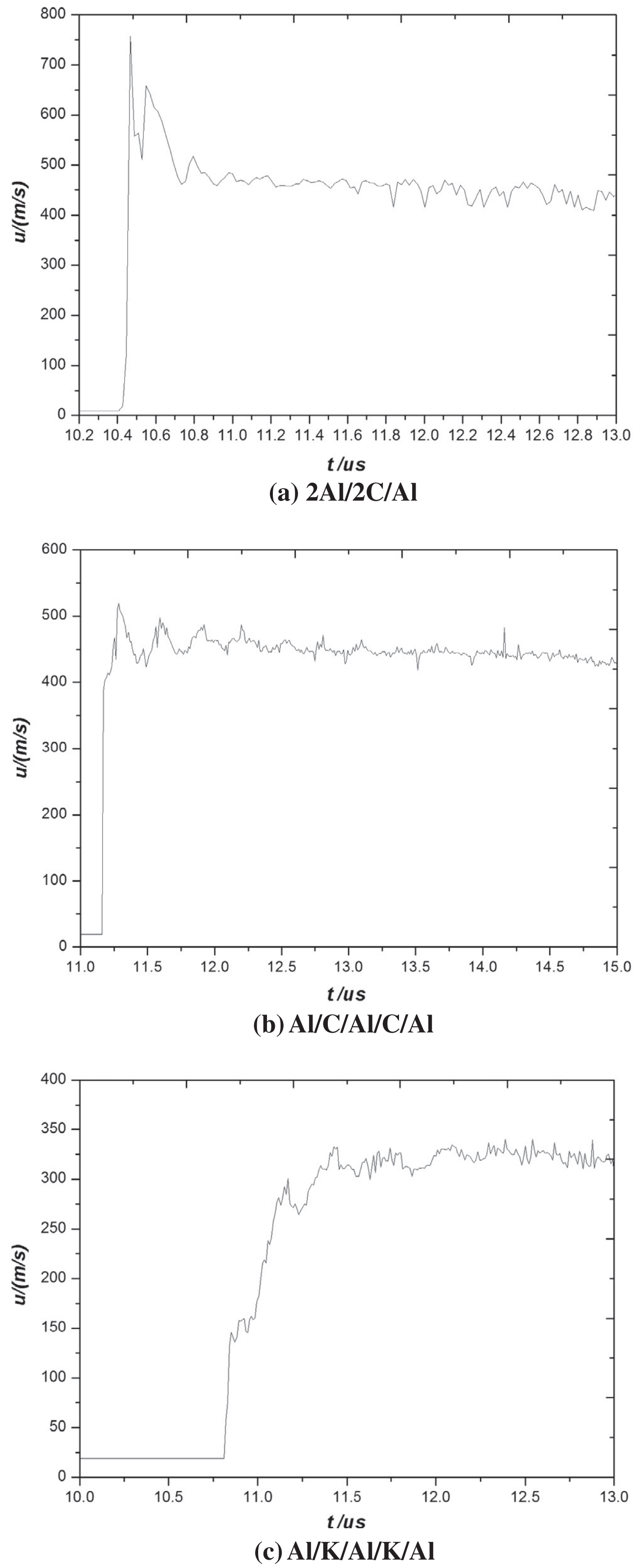


Fig. 9. Velocity profiles of the free surfaces of the hybrid laminates. (a) 2Al/2C/Al; (b) Al/C/Al/C/Al; and (c) Al/K/Al/K/Al.

Based on the observations of the damages of the impacted targets and their free surface velocity profiles, it can be concluded that the aluminum alloy/composite interfaces widen the shock front and dissipate the shock intensity simultaneously. The results

are consistent with the findings from Zhuang et al. [24], who has comprehensively studied the shock response of alternately placed biomaterial specimens and found that if the total mass of each component was kept unchanged, increasing the interface number of the laminate by reducing the layer thickness resulted in increased dissipation of shock energy and transformation of kinetic energy to internal energy.

The analysis of the damage profiles and the free surface velocity profiles of the targets disclose that the extent of the damage from HVI is correlated with the free surface velocity profile of the target. The lower the peck velocity, the less possibility perforated damage occurs. Moreover, the extent of bulging deformation of the laminate due to kinetic energy concentration is associated with the plateau value of the velocity profile. For the specimens labeled 2Al/2C/Al, 1Al/2C/2Al, Al/C/Al/C/Al and Al/K/Al/K/Al, the velocity plateaus were approximately 480 m/s, 460 m/s, 450 m/s and 350 m/s, respectively. The corresponding heights of the bulges for these specimens were 11.8 mm, 9.9 mm, 9.2 mm and 7.0 mm, respectively. It is means that the stacking of aluminum back plate has more efficiency in reducing kinetic energy concentration for the three layered laminates. Ramadhan et al. [10] also investigated the sequence of Al plate position (front, middle and back) inside Kevlar-29/epoxy and 6061-T6 aluminum laminate plates and found that the Al back stacking sequence plate for overall results obtained was the optimum structure to resist the impact loading. The five-layered Al/KERP laminate had the best shielding performances on HVI and correspondingly the lowest peak velocity and the lowest velocity plateau among the tested specimens.

4. Conclusions

In this work, ballistic tests of 2024 aluminum alloy panel, CFRP composite panel and their hybrid laminates were carried out, using an electric gun to launch Mylar flyer at velocities over 9.0 km/s and a laser velocity interferometer to measure the free surface velocity profile of the specimens on HVI. Experimental results show that the aluminum alloy panel and the CFRP composite panel are damaged in quite different manners, ductile damage with a high-speed spall film for aluminum alloy and fragile damage with a thorough perforated hole for CFRP. Shielding performances on HVI was improved by the design of hybrid laminates that consisted of aluminum alloy and CFRP/KFRP layers alternately. For the Al/CFRP sandwiched laminates, the peak shock pressure was significantly reduced, although they were perforated by the flyer. Comparatively, the five-layered aluminum/composite laminates resisted HVI under the same condition without perforation. The Al/KFRP laminate demonstrated the best shielding performance on resisting HVI among the tested specimens, which was attributed to scattering of the shock wave by the internal interface and absorbing of the shock energy by the good toughness of KFRP. Furthermore, the extent of the damage for the after-impact specimen was correlated with the free surface velocity profile. The lower the peak and the plateau of the free surface velocity, the lower the shock intensity and the kinetic energy concentrated in the impacted zone. The planar impact testing with an in-site free surface velocity measurement provides a feasible way for quantitative evaluation of the shielding performance of a material.

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